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1968-29

**A Concept
for Air Traffic Control**

H. G. Weiss

17 October 1968

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MASSACHUSETTS INSTITUTE OF TECHNOLOGY
LINCOLN LABORATORY

A CONCEPT FOR AIR TRAFFIC CONTROL

H. G. WEISS

Division 4

TECHNICAL NOTE 1968-29

17 OCTOBER 1968

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ABSTRACT

To increase the number of aircraft which can operate safely in high traffic areas and to expedite traffic at busy airports, it is proposed that each commercial flight travel from terminal to terminal along a "flight tube" reserved for its exclusive use. To make this possible, an instrumentation system is described which would continuously provide an aircraft with both accurate position information and with instructions for progressing along any selected "flight tube." Every few seconds each aircraft would report its identity, position and altitude via a digital air-to-ground data link to the Air Traffic Control (ATC) centers. This accurate, unambiguous information will enable the centers to monitor automatically all aircraft movements, and any deviation of an aircraft from an assigned flight plan would be detected by the computer and brought to the attention of the appropriate ATC controller.

Because the navigation and position reporting would be automatic, the work loads now experienced by the air crews and the ground controllers would be reduced. Congestion at airports and stacking of aircraft near airports would be minimized by continuous forecasts of runway availability and by en route adjustments of the time of arrival of an aircraft at its assigned runway. A compatible capability, at lower cost, is proposed to enable the ATC system to track automatically all private and general-aviation aircraft.

The proposed navigation and data reporting system would also function during takeoff and landing as well as en route, and would obviate the need for the existing network of omni-ranges, localizer beacons, ground radars, landing systems and other navigation aids. It would provide data of high quality on aircraft movements and enable the computerized data processing system now being introduced throughout the country by the Federal Aviation Administration to operate with greater effectiveness. The precise navigation, control and scheduling which is provided by the proposed system would enable higher densities of aircraft to operate safely and would permit new runways within the confines of existing airports to be used effectively.

Accepted for the Air Force
Franklin C. Hudson
Chief, Lincoln Laboratory Office

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A CONCEPT FOR AIR TRAFFIC CONTROL

I. INTRODUCTION

The rapid growth of air traffic has severely strained the system used by the Federal Aviation Administration (FAA) for the control of aircraft, and the difficulties now being experienced are likely to be greatly exacerbated in future years. Each week approximately 9 commercial and 100 general-aviation aircraft are placed into service, and the continuing expansion of the aviation industry seems inevitable (Fig. 1). Commitments in excess of \$11 billion have

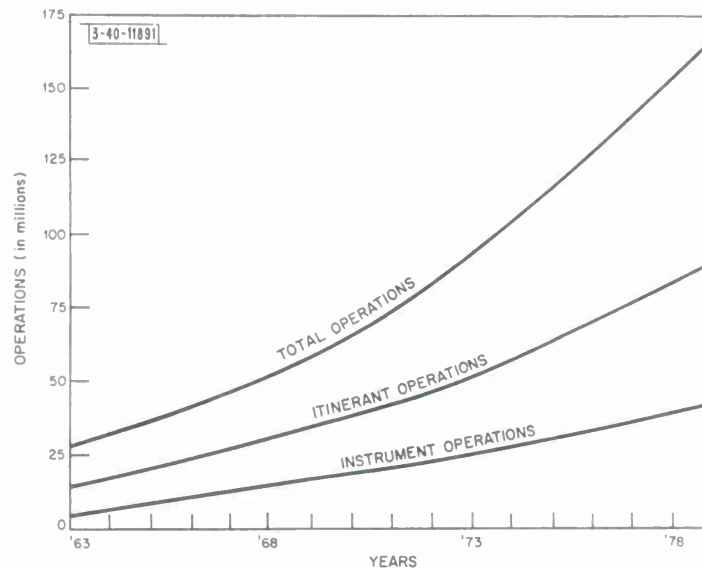


Fig. 1. Total itinerant and local aircraft operations at airports with FAA traffic control service (Ref. 1).

already been made for new commercial airplanes to be delivered during the next four years, and even larger investments in air terminals and support facilities are likely during the next decade. Because efficient air transport is important to the growth and economic health of the nation, a large investment for an improved air traffic control (ATC) system would be justified if it could increase the ability to move passengers and aircraft with economy and safety.

About 10 years ago plans were outlined for introducing high-speed computers, displays and automatic data transmission facilities into the ATC system.²⁻⁴ Although this program has been proceeding slowly, due in part to fiscal limitations, automated ATC centers are starting to

become operational. During the next four years, a complete network of computer systems for ATC should be in operation within the United States.

One of the major limitations of the present ATC system stems directly from its heavy dependence upon controllers on the ground who participate in the generation, interpretation and dissemination of information needed for directing aircraft movements, particularly near airports. Because the present system of radars, navigation aids and position reporting does not provide precise, automatic and unambiguous information either in the aircraft or on the ground, substantial human intervention is required. The resulting work load on the ATC controllers and pilots is one of the limiting factors on the density of aircraft which now controls air space utilization.

The ATC problem is compounded because there are only a limited number of airports which can be employed to provide effective service to large metropolitan areas, and it does not seem possible to greatly alleviate the problem simply by constructing additional airports near large cities separated by distances of less than 20 or 30 miles since, of necessity, they will still share common air space. With aircraft now moving at speeds of 8 to 10 miles per minute, it seems essential to consider the air traffic in areas perhaps as large as 1000 x 1000 miles in a fully integrated manner.

The information now available to supply the ATC network consists of flight plans, radar information from a network of ground-based radars (called primary radars) and beacon transponders (called secondary radars) on aircraft and voice communications between the pilots and controllers. Although there has been extensive work to refine radar systems for ATC applications, practical surveillance radars still have resolution limitations, do not provide good altitude or identity information and suffer from weather and other sources of interference. The altitude and identity data provided by airborne transponders are far from adequate in quality for use in heavily congested areas. While the advanced computers and display techniques being introduced will undoubtedly improve the control of air traffic, the quality of data which feeds the automatic data processing system remains inadequate; therefore, the controller is likely to remain as a critical element in the system. To make the ATC system more effective, it is believed that it must be provided with improved data sources so that it will be more automatic in operation. Human intervention and judgment should be minimized and reserved for nonroutine circumstances. Since there are now 14,000 controllers engaged in the operations of the ATC system, substantial savings in personnel costs could be an important byproduct of a next-generation system.

II. DISCUSSION OF CONCEPT

To overcome many of the problems which have arisen as a result of the increased number and speed of aircraft, a new ATC concept is proposed. It is based upon fundamental changes in the present philosophy and technical capability including:

- (a) Aircraft should be equipped to travel between terminals with little or no voice dialogue between the aircraft and the ground controllers. To attain this capability, it is proposed that the aircraft fly on a reserved path through airspace (flight tube) which would insure noninterference with other aircraft. This requires improvements in the ease and precision with which an aircraft can navigate in accordance with a preselected flight plan.
- (b) Aircraft should be equipped to send automatically to the ATC centers accurate reports at frequent intervals on their identity, position and

altitude in a format which can be utilized directly by the ground computers. With this type of information, the ATC system will be able to keep continuous track of all aircraft movements and compare them to assigned flight patterns. The controllers can then operate in "shunt" and not in "series" with the large quantity of rapidly changing data on aircraft movements.

- (c) Automatic forecasting of runway availability and en route scheduling should be used to increase the utilization efficiency of runways and to eliminate stacking near terminals.
- (d) With improved navigation, control and scheduling, the spacing between runways may be reduced and additional runways can be constructed at existing airports to increase the total flow of air traffic.

It is proposed that commercial air traffic be automatically time-sequenced along a network of accurately defined "flight tubes" which do not intersect in air space, except during the actual takeoff and landing phases of the flight. Each flight tube would start on the runway at the take-off position and would define a continuous path to be followed by the aircraft until it landed on the runway at the distant airport. Modern instrumentation now permits aircraft to be precisely routed both in position and in time along any preselected "flight tube," and because the location of the axis of each "flight tube" can be determined with an uncertainty small compared with the size of an aircraft, a very large number of aircraft can progress safely through three-dimensional space. The system would be designed to accommodate diversions due to weather, unanticipated congestion at runways, etc.

The proposed system should be contrasted to the air corridor routing, which is currently in use (Fig. 2). In the present system many aircraft fly along comparatively wide corridors which concentrate traffic over ground navigation aids, whereas in the proposed system the "flight tubes" would be dispersed and aircraft would not utilize common air space except when within about five minutes of an airport. Consequently, aircraft movements would not be interdependent, except for this short interval of each flight.

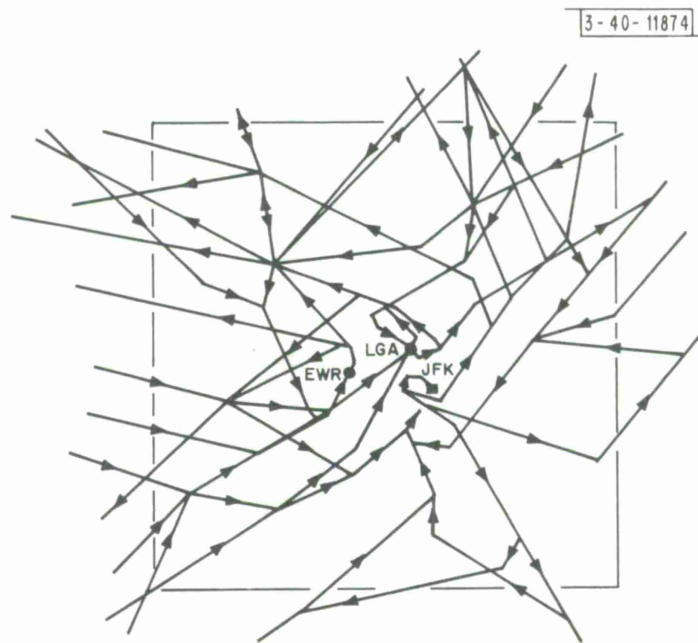


Fig. 2. New York airspace routes, 1965 (Ref. 5).

Since the ATC system would know each flight tube assignment, and a data link would relay position and identity reports automatically, the computers at the ATC centers will be able to monitor continuously if an aircraft is proceeding along a safe path. This system would eliminate the need for most of the critical and difficult real-time decisions which now face the ground controllers and would place them in "shunt" and not in "series" with the continuously changing flow of data on the movement of aircraft. It also offers promise of replacing many of the navigation aids, beacons and ground radars in the present system. It will allow a higher density of aircraft to arrive and depart safely and expeditiously from existing airports. The cost of the proposed system is not greater than the investment in the present system, and seems fully commensurate with the economic importance and the benefits that should accrue from the more effective use of aircraft and airport facilities.

Except when near an airport, the tubes in the proposed system would be somewhat analogous to the strands in a bowl of spaghetti, which intermingle but do not intersect each other. Because aircraft can be instrumented to accurately maintain their assigned positions in flight tubes and to progress along tubes at a specified rate, the total number of aircraft permitted in a high-density area can be increased substantially. The availability of runways and other terminal facilities, rather than considerations of aircraft control and safety, will ultimately limit the movement of aircraft. By coordinating the arrival and departure phases of the flight, the peak traffic capacity at airports could be increased greatly, since with this improved control and instrumentation the spacing between parallel runways can be reduced. With proper time sequencing, runway separations of only 1000 feet appear to be possible.

To minimize the enroute traffic coordination task, a very large number of flight tubes will be required. For example, it may be necessary to provide independent flight paths from a large metropolitan airport to approximately 100 different cities. To allow for weather differences in the flight characteristics of various types of aircraft and accommodations for peak traffic loads, each of these 100 distant cities may require from 30 to 200 flight tubes. Therefore, as many as 10,000 flight tubes will have to terminate in the vicinity of a large airport. Because each flight tube can be considered independent when its axis is separated by more than 500 feet from any other flight tube, this large number of discrete flight tubes can be accommodated in the region of the sky about 15 miles from an airport. At this distance from the airport, aircraft will already be distributed in altitude between about 4,000 and 16,000 feet. En route, where the density of aircraft will be substantially lower, the flight tubes can be much farther apart. In planning these flight tubes, it is necessary, of course, to limit lateral aircraft accelerations to less than 0.1 g for passenger comfort and to utilize only flight profiles which can be readily achieved with existing classes of aircraft.

The en route flight tubes, which would terminate about 15 miles from an airport, could be visualized as an array of ports on the wall of a hypothetical right circular cylinder. Separate angular sectors around the cylinder would be reserved for approaches and other sectors would be utilized for departures. For travel between two major cities, such as Washington and Boston, as many as 200 flight tubes would be allocated. These 200 tubes would provide for low, medium and high altitude routes, as well as for direct great-circle flights and for routes north and south of the direct route for accommodating weather patterns. In addition, there would be a number of separate but essentially similar routes for accommodating peak traffic requirements.

Aircraft flight paths within the terminal area would follow specific flight tube assignments so that each aircraft would progress through the region in a rigorous manner. To simplify the

bookkeeping task, all terminal maneuvers could be referenced to the appropriate touchdown or departure point and the runway axis. Each of these patterns would be designated by a specific index number within the flight file.

To enable the pilot to stay on his pre-assigned "flight tube" he will, at all times, be presented with a very accurate but simplified display which will inform him continuously of the action he must take to maintain his progress within and along the assigned path through space. This display will indicate if the aircraft should: (a) maintain a steady course, (b) turn right or left, (c) climb or descend, or (d) proceed faster or slower. To allow the pilot to control his aircraft accurately, the display indications would be proportional to the required response to maintain the desired position in space.

Because at all times there will be accurate and up-to-date information, both in the aircraft and on the ground, of the position of each aircraft, a system can operate with a minimum of intervention by the ATC ground controllers. Except when near terminals, aircraft will be able to travel from departure to landing without encroaching on the "zone of safety" of any other aircraft. The avoidance of conflict in the terminal area would be accomplished by assignment of flight patterns and time schedules by the ATC centers.

III. APPLICATION OF RECENT TECHNOLOGY TO ATC

It now appears possible, by exploiting recent advances in electronic technology, to provide an ATC system capable of fulfilling the more rigorous requirements of the next few decades. The foundation of the proposed system rests upon the use of precision timing, nanosecond coding techniques, and digital data links, data files and computers in aircraft. This instrumentation would be used to provide up-to-date information to the pilots in the aircraft and the ATC centers on the ground.

It is suggested that it is now technically feasible to develop airborne instrumentation which can receive accurately timed signals from a network of ground radio transmitters and process this information in a small computer to determine continuously its position with very high precision. It is also suggested that a small data file on magnetic tape can store all the information required to define many "flight tubes" and the data can be compared with the position information to generate instructions to the pilot on the actions which he must take to fly with high precision along an assigned flight tube. The continuous reporting of aircraft identity, position and altitude via redundant paths to the ATC system by the use of a digital data link would replace the less adequate data which are now obtained from the primary and secondary radar systems.

Very accurate position information is required to move aircraft through regions with high traffic density safely and to land aircraft on schedule under conditions of poor visibility. It is obvious that for landing and taking off under conditions of essentially zero visibility, the position errors must be small (~10 feet) compared to the width of the runway. For transit through highly congested areas, the position of all aircraft relative to a common coordinate system should be known continuously, with an uncertainty not much greater than the physical size of the aircraft (~100 feet). Ideally, the instrumentation for determining aircraft position should be self-contained within the aircraft and independent of radio signals or other ground-based aids. Inertial and Doppler navigation systems have high precision, but they accumulate position errors with time and are not sufficiently accurate after several hours of flight for landing aircraft under conditions of zero visibility without assistance from ground-based terminal aids.

An ATC system dependent primarily upon the use of ground-based radar information is not likely to be adequate for the high traffic density situations which will prevail during the next decade. Radars have difficulties in providing continuous coverage, unambiguous aircraft identity, high angular resolution, freedom from radar clutter, accurate height information and adequate data rate. While many of these difficulties could be overcome by the use of improved instrumentation and aircraft transponders, radar systems have obvious technical limitations in highly congested areas where many aircraft are engaged in frequent maneuvers and where the data requirements become high. There are also psychological factors which militate against the use of these systems, since every pilot likes to know the position of his aircraft at all times without dependence upon the response of personnel or instrumentation on the ground. However, systems which rely upon the transmission signals from ground-based radio transmitters, which broadcast signals to all aircraft and are therefore unaffected by the number of users, are suitable for use in future systems, providing there is adequate redundancy in the ground facilities and providing there is suitable instrumentation in the aircraft to augment the information available from the ground navigational aids. The use of hybrid systems involving both on-board instrumentation and ground navigation aids will probably prevail, because they provide complementary flight and safety capabilities.

A. Airborne Computers

One of the most basic advances in electronic technology which will have a major influence on aircraft navigation and control stems from the feasibility of employing high speed digital computers in aircraft. The use of these digital computers opens up many new system concepts, since data can be accepted from different sources and can be manipulated with high speed, precision and flexibility. In addition, large quantities of information can be retrieved rapidly from storage memory, particularly if the information is systematically organized and catalogued. Airborne computers can now be constructed which have high reliability, small size, low power requirements and a cost commensurate with that of other electronic systems used in aircraft. With integrated electronic circuits and the latest miniaturized memory units, a versatile, high speed, moderate-capacity digital computer can be packaged in less than two cubic feet of space.

B. Nanosecond Pulse Technology

The technology associated with the generation and utilization of nanosecond pulses has also progressed markedly in recent years. Experimental radar systems are in use which are capable of resolving, in range, targets which are less than one meter apart at distances of greater than 100 miles. Solid state electronics has made it feasible to construct low cost, low power circuits with sufficient bandwidth and stability for reducing timing errors to only a few nanoseconds.

C. Precision Clocks

In recent years timing standards have become more precise and comparatively inexpensive. Rubidium and cesium beam clocks are now commercially available which, with 1 second averaging, are capable of stabilities of 5 parts in 10^{-12} (Ref. 6). The availability of these components makes it feasible for ground stations without interconnecting links to radiate synchronized transmissions for periods of up to two days with timing uncertainties not greater than 100 nanoseconds. Hydrogen beam timing standards⁷ capable of stabilities of about 3 parts in 10^{-13} are in development and should permit remote ground stations to operate for periods of

up to 10 days with timing uncertainties of not greater than about 50 nanoseconds. During the next 5-year period, it is probable that clocks will improve and permit remote clocks to remain synchronized to within 50 nanoseconds for periods of up to 2 months. Various methods for standardizing clocks by the use of transportable reference standards and by aircraft and satellite transponder systems are under active investigation.⁸

Radio waves in free space propagate at a velocity of 299.793 meters per microsecond (approximately 1 foot per nanosecond). At very low elevation angles in the earth's atmosphere where the propagation variability is greatest, the propagation velocity of line-of-sight radio signals in the 1- to 6-GHz region of the spectrum is constant to within 2 parts in 10^4 of the path length.⁹ Consequently, if timing instrumentation errors could be eliminated, it would be possible to measure the time of arrival of radio signals in even a low flying aircraft from a ground transmitter with an uncertainty of about 50 nanoseconds (50 feet) over transmission paths of 50 miles. Because these propagation errors are partially predictable, radio distance measurements in practice can be accurate to 20 feet or less. Measurements made over 50-mile-long transmission paths which have elevation angles a few degrees above the horizon will have propagation uncertainties of 1 part in 10^5 or less, and distance can be measured with uncertainties of 5 feet or less.

D. Position Determination by Time-Difference Measurements

Navigation systems such as GEE and LORAN,¹⁰ which permitted aircraft and ships to determine their position by the measurement of the relative time of arrival of signals from three or more time-synchronized ground transmitters came into use during World War II. Even in this time period it was possible, on a routine basis, to obtain position fixes accurate to a few hundred yards when within 100 miles of the GEE stations. While these systems were not sufficiently accurate for the determination of aircraft height, recent improvements in precision clocks and nanosecond timing technology, when coupled with the proper choice of radio frequency and ground station geometry, now permit this capability.

The addition of the digital computer to automatically and continually identify ground station codes and to accurately and rapidly perform computations which involve the precise coordinates of ground stations provides a substantial new capability for the navigation and control of aircraft. Redundant data from more than the minimum number of ground stations required for a position determination can also be processed in the computer to optimize performance. In addition, the computer can be used to convert the time-difference information into a coordinate system easily interpretable by the pilot. This capability could not have been realized with sufficient accuracy for navigation in high density areas and for landing and taxiing aircraft only a few years ago.

The proposed concept, which uses technology similar to the recently described Air Force CNI (Communication, Navigation and Identification System),¹⁰ is basically different because it uses a grid of comparatively closely spaced ground stations and does not rely upon satellites for relaying timing and communication information. In addition, it employs increased bandwidths, higher data rates and a flight control philosophy that is better matched to the control of traffic at congested airports.

IV. SYSTEM DESCRIPTION

A. Determination of Aircraft Position

It is proposed that commercial jet aircraft be instrumented to automatically and continuously determine position by measurement of the difference in the time of arrival of pulses radiated from a grid of ground stations. A similar system, but with the computation done on the ground, is proposed for small aircraft (see Sec. V). While the system proposed for large aircraft is conceptually similar to that used in GEE and LORAN,¹¹ it would be far superior in performance because of the more precise synchronization of the ground stations, the utilization of a common carrier frequency of all ground stations thereby eliminating tuning of the airborne receiver, the use of digital identity codes associated with each ground transmission and the automatic processing of the signals by means of an on-board digital computer. The computer would also serve to convert the position determination from the hyperbolic coordinates obtained from the ground grid to a latitude-longitude coordinate system suitable for use on a worldwide basis. The timing precision and ground station separations have been chosen to provide altitude information throughout most of the flight path which can augment information provided by on-board altimeters.

B. Functions Performed Within the Aircraft

The functions which will be performed within the aircraft are:

- (1) Automatic determination of aircraft position.
- (2) Selection from the computer file of the coordinates of the assigned flight path in time sequence at a preset rate.
- (3) Display of instructions to the pilot.
- (4) Transmission of the identity and position of the aircraft to the ATC centers at a frequent rate.

Each of these functions, which are shown in Fig. 3, will now be described.

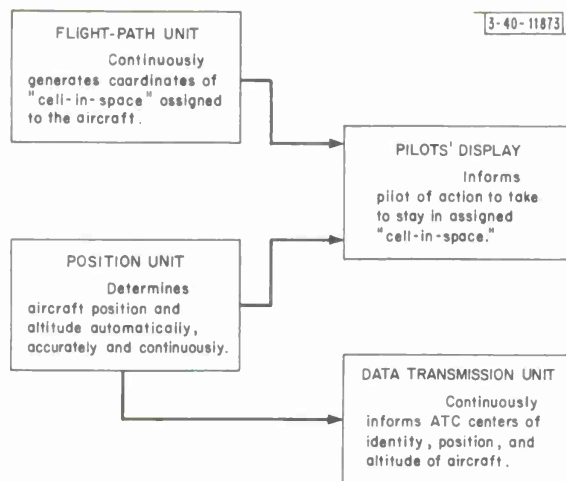


Fig. 3. Airborne equipment functions.

1. Position Determining Unit

It is proposed that a coordinate system be established to permit the coding of air space in three dimensions with a discrete digital address for each "cell in space." The position address of an aircraft will consist of three sets of digital numbers corresponding to its N-S, E-W and

altitude coordinates. The functions of the position unit are to determine automatically the position and altitude of the aircraft and convert this into a coordinate address. This unit in the aircraft would operate unattended and would achieve its reliability by using all solid state components and by having no knobs, switches or moving parts.

To enable the position unit to provide data suitable for taxiing on the ground during periods of low visibility, as well as for takeoff and landing, it is proposed that the position determination be very accurate. In addition, high accuracy will permit flight tubes to be closely spaced in regions where a high density of aircraft must be accommodated. The accuracies and data rates shown in Table I have been selected to be compatible with the performance which can be demonstrated in a test system within 18 months. With the indicated accuracies, errors contributed by the position determining system will have only a minimal influence on the permissible minimum separation between contiguous flight tubes.

TABLE I ACCURACY AND DATA RATE OF AIRCRAFT POSITION DETERMINATION		
Location of Aircraft	Accuracy of Determination of Latitude and Longitude (ft)	Interval Between Successive Position Determinations (sec)
On runway and within 2 miles of airport	~ 15	0.2
Within 10 miles of airport	~ 30	1
En route	~ 60	5

The accurate and automatic determination of position is determined by measuring, in the aircraft, the differences of the time of arrival of signals transmitted by a network of synchronized ground stations. As described later, these signals would be coded with identity tags, and therefore can be processed automatically in a small airborne computer to yield accurate position information. The accuracy is limited primarily by the synchronization, precision and geometry of the ground stations.

2. Flight Path Unit

The flight path unit will contain a digital data file comprising a large repertoire of pre-calculated flight paths which could be utilized for travel between air terminals. This unit will sequentially produce the digital addresses of the position coordinates along the desired flight path.

The assignment of a flight path and a proposed arrival time at the distant airport would be made by the FAA just prior to departure. Selection of the flight path and the arrival time would be chosen by a computer in the FAA control center to minimize flight congestion, with due regard for aircraft performance characteristics, known weather factors and the availability of runway space at the distant airport. The pilot would introduce this information into the flight path unit by a series of push buttons.

The coordinates of the assigned flight path would start on the taxiway at the airport prior to takeoff and would be generated in a continuous stream until arrival on the ground at the remote airport. The rate at which these addresses would advance would depend upon the assigned flight plan which would take into account aircraft characteristics, weather, runway availability at the remote airport, etc. The rate could be changed in a simple manner by selection buttons. All such changes would be made only after coordination with the ATC centers to eliminate conflicts with other aircraft.

Each segment of a flight tube would have a unique file number and consist of a string of pre-programmed sequential positions stored in the files of the airborne and ground-based computers. A typical flight tube would consist of at least five segments which would include a takeoff sequence, a short connecting segment to join the runway with the designated en route flight tube, an en route sequence, an approach sequence and a landing sequence. In addition, the desired time of arrival at the distant runway would also be assigned and would determine the speed of the aircraft throughout the midroute phase of the flight. Because the movement of the aircraft along its assigned flight path is within a control loop with continuous feedback, it should be possible, if the weather and wind conditions are about as anticipated, for the pilot to arrive at the runway approach point within ± 5 to 10 seconds of his assigned time. If the initial predictions are not fulfilled, a new arrival time would be assigned en route by the ATC controller. Since for any given class of aircraft there are only a limited number of desirable position-vs-time routines for the takeoff and landing phases of flight, and since these routines can readily be referenced to the coordinates of any runway in the United States, the total data storage requirements are nominal and can easily be incorporated into a computer system.

The system will be designed to be fully functional while the aircraft is on the ground, and therefore both the pilot and the airport controller, who would have a remote display from the nearest ATC center, will be able to monitor independently the operational status of the equipment in all nearby aircraft, as well as the ground beacons near the airport. This is an important safety feature of the system.

If unplanned conditions develop while the aircraft is en route because of weather, equipment malfunctions, etc., the FAA control center could reassign a flight path and arrival time and the flight path unit would quickly and conveniently generate a continuous flow of cell coordinates in accordance with the revised instructions. When the aircraft is within 20 to 30 minutes of the terminal airport, the FAA ground controller could reconfirm or modify the arrival time at the approach path, so there would be no "stacking" in the vicinity of a terminal. Time delays could be introduced by varying the speed of the aircraft, since jet aircraft can fly between 300 and 550 mph if required. Alternatively, the aircraft could fly on a preprogrammed "race-track pattern" whose duration would be computer controlled to bring it out of the turn precisely with the prescribed time delay.

This concept permits the specific flight characteristics of each class of aircraft to be introduced into the flight profiles in the optimum manner. These flight characteristics will, of course, change dramatically with loading, fuel burnoff, etc., but can be predicted with reasonable accuracy for any given type of aircraft prior to takeoff on any specific operation. Such characteristics as rate of climb and turn, optimal speed, etc., would be introduced into the flight tube unit. Since the file will be on magnetic tape, disks, or equivalent device, the file repertoire can be very large and readily modified whenever flight paths are changed, beacons added to the ground network, runways modified, etc. To simplify the quantity of information

which will have to be stored in the flight path unit, the airborne computer could be used to interpolate between coordinate values stored in the file.

3. Pilot's Display Unit

The pilot's display unit would operate from the data generated by the position and flight path units and would convert this information into simple instructions to the pilot. The pilot's display would indicate whether he should go up or down, right or left, or faster or slower to stay on the assigned flight path and to progress along the route at a prearranged rate.

With this proposed system an aircraft flying between two air terminals (for example, Boston and Denver) would always stay within a few hundred feet of his assigned flight tube and would progress along the tube within perhaps only 5 to 10 seconds of his assigned rate. The arrival at the distant terminal should take place within 5 or 10 seconds of the previously designated time — even though the time might have been selected perhaps 3 hours earlier, just prior to takeoff. Because accurate data on the progress of each aircraft will be available at the ATC centers, the forecast of the arrival rates for each major airport can be updated periodically and traffic flow regulated well in advance of the actual arrival at the airport. Therefore, aircraft would not accumulate near airports to be stacked awaiting landing instructions; but their assigned flight trajectories would bring them to the runway on one smooth, continuous approach sequence.

The degree of precision suggested for the proposed system, while perhaps appearing incredible, should be attainable because the pilot is always within a continuous feedback command-control loop. In some ways the situation is analogous to the control which is achieved routinely by automobiles traveling in opposite directions along a narrow country road. Experience indicates that cars with relative closing velocities of perhaps 80 to 100 mph can pass within 6 feet of each other without undue driver skill or effort. This is because the driver has a continuous reference system which permits him to accurately gauge his position on the roadway with respect to his desired path, and he is in a proportional control loop which allows him to "stay in the groove." An equivalent situation should prevail with the use of the proposed system.

4. Data Transmission Unit

To permit the ATC centers on the ground to monitor all air traffic continuously, a data-remoting unit would be placed on each aircraft to transmit automatically information to the ground at frequent intervals. The information would be transmitted in digital format and include the aircraft identification number and the position and altitude of the aircraft. The interval between transmissions would be reduced when an aircraft was near an airport. The reports at the ATC centers should always be accurate and up to date. In the event that the airborne electronic equipment failed, an alternate mode of operation, described in Sec. V, would permit continuous data to be maintained.

Since the ATC centers on the ground would know the "flight tubes" assigned to each aircraft, the ground computers would monitor and compare the aircraft position with the assigned flight coordinates and indicate all deviations from preassigned routines. Because there would be reports from the aircraft at frequent intervals (at least once each 5 seconds), the need for ground-air voice communications would be greatly diminished and voice communications would be used primarily for changes in flight assignment or for emergency instructions between pilot and ground controller. In principle, an aircraft would be able to fly a complete terminal-to-terminal mission

lasting several hours with only one ground-to-aircraft transmission at the time the plane receives clearance for takeoff and another when the aircraft is approaching the distant terminal. If desired, a digital data link could be used for these messages instead of a voice link.

It is important to note that the ground controllers at the ATC center would be in "shunt" with the traffic flow and not in "series." They would have full access to everything that is going on and will continuously monitor all aircraft movements. However, they would play an active role only when a plane deviates from its previously assigned flight path or when, because of storms, equipment malfunctions, etc., they must provide new instructions to the aircraft.

In principle, it would be relatively easy to connect the data feeding the pilot display unit directly to the auto-pilot of the aircraft, but there are both practical and psychological reasons which militate against this mode of operation except at the pilot's discretion. However, because the proposed system greatly reduces the demands on the pilot, since he no longer has to be occupied with the determination of position, the planning of future course changes or with frequent voice contacts with the ground, his role becomes somewhat analogous to that of an operator of a subway train who is attempting to arrive at designated stations according to the preassigned schedule. The pilot should therefore be better prepared to monitor his aircraft status, visually watch for other aircraft and cope with emergency situations.

C. Functions Performed on Ground

The proposed concept employs ATC centers which would be functionally similar to those now in operation. However, the operations of the center would be improved and the manpower greatly reduced, since the automatic data system at the center would receive frequent and accurate messages in digital format from each aircraft, and these messages would include the aircraft identity, position and altitude. The quality and frequency of this information will permit the ATC centers to process and display the position and status of all aircraft in the sector without the need for substantial filtering or augmentation by human operators.

Since the ATC centers would know the flight tube assignment for each aircraft and have accurate information on both the desired and actual positions and progress of each aircraft along its flight tube, they can continuously monitor the air traffic. If an aircraft deviated from its assigned flight plan, this occurrence would be detected by the ground computer and tagged for appropriate action, either by an ATC controller or perhaps directly through an automatic data link to alert the aircraft.

Under normal operations, there should be little need for ground controllers to communicate with an aircraft providing it progresses along its flight tube in the prescribed manner. In addition, since the ATC operator will be in "shunt" and not in "series" with the movement of aircraft, many of the present difficult coordination and hand-over problems within the ATC centers should be minimized.

Flight information of direct interest to a control tower at an airport would be transmitted over telephone lines and presented to the control tower operators. These data would identify and show the exact up-to-date position of each aircraft near the airport and also show its deviation from its assigned flight path. If flight operations are functioning in the normal manner, it should not be necessary for the airport control tower to make voice contact with an aircraft throughout the complete landing maneuver.

An alternate concept for use with commercial aircraft would be one in which the aircraft position would be computed at the ATC centers in the manner proposed for private aircraft (Sec. V). While this would eliminate the need for airborne computers, it would require the addition of a ground-to-air data link and appears to have obvious limitations in high traffic density areas near airports where the data rate requirements may be high. It also seems desirable for each aircraft to have continuous knowledge of its exact position coordinates without reliance upon a ground-to-air data link. This alternate mode of operation would always be available for use if any part of the main navigation system failed and would provide a redundant capability (Sec. VI).

When the proposed system becomes operational, ground radars located near airports and throughout the air routes could be used to provide the computers at the ATC centers with a redundant source of aircraft position reports. These reports would, in turn, serve to check on the operation of the ground stations, as well as on the navigation and position-determining equipment in each aircraft.

Movement of passengers and baggage at air terminals is most difficult when there are traffic delays during peak load periods. These problems could be minimized by the precise scheduling that becomes possible by the use of the proposed system.

D. Description of Ground Stations

Typical geometry for the ground stations is shown in Fig. 4. Measurement of the differences in the arrival times between four or more ground station signals (Fig. 5) would allow the position and altitude of the aircraft to be determined. The waveforms radiated by these ground stations are shown in Fig. 6. Table II lists the nominal separation between stations, the timing accuracy and the interval between transmissions for these ground stations. The grid is sufficiently dense so that an aircraft would receive signals at all times from at least 4, and perhaps in some cases as many as 10 to 15, ground stations. However, since each ground station transmits an identity code and since the computer within the aircraft has accurate knowledge of the position of the aircraft with respect to the ground stations, it can easily search for those specific four stations of primary importance and perhaps one or two others which would be used for data smoothing and for redundancy.

It is proposed that all the ground transmitters operate at the same nominal wavelength so that signals from all ground stations within range of the aircraft will be received without any receiver adjustments. Each transmitter would be pulsed on for only about 2 μ sec; with a keying interval of either 5, 1 or 0.2 sec, depending upon its location with respect to an airport. While the duty cycle of any transmitter is very short ($\leq 10^{-5}$), if the stations all pulsed at the same time, occasionally signals from two or more ground stations will arrive at the receiver simultaneously. The equipment in the aircraft could be designed to reject these overlapping signals. A few seconds later the signals from these stations would separate in time because of the movement of the aircraft. This interference can be eliminated by staggering the exact keying times of nearby stations within the 5-, 1-, or 0.2-sec interpulse intervals.

Within each 2- μ sec transmitter pulse, there would be approximately 20 subpulses, each approximately 100 nsec in duration, which would carry a unique identity code for each ground station. The exact coordinates of each ground station would be incorporated into the computer memory in the aircraft. Although there will be the coordinates of a thousand or more ground

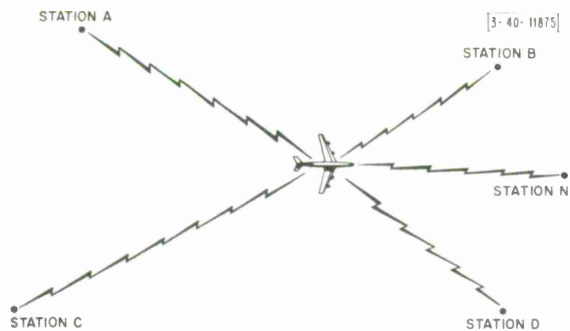


Fig. 4. Typical ground station geometry.

Fig. 5. Output of aircraft receiver.

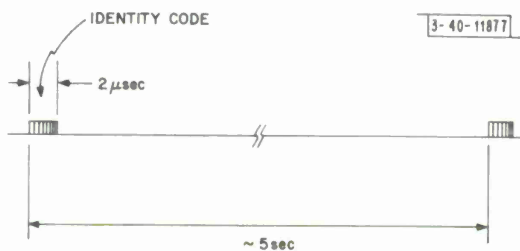
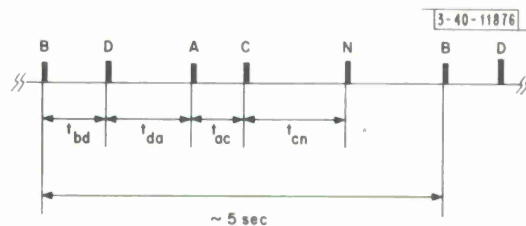


Fig. 6. Typical ground transmitter waveform.

TABLE II GROUND STATION CHARACTERISTICS			
Location	Nominal Station Separation (miles)	Timing Accuracy (nsec)	Interval Between Transmissions (sec)
En route Stations	75	60	5
Near Airports	10	30	1
At Airports	2	15	0.2

stations in the computer memory file, for every region of the country, only a small number of stations is of interest and the computer system can preselect and have available the appropriate station coordinates for subsequent processing operations.

It is proposed that all the ground stations radiate at an assigned wavelength between 2 and 4 GHz. The spectrum bandwidth for the 20-nsec pulses will be about 50 MHz. The equipment at each ground station would be relatively conventional and consist primarily of all solid state components, except for perhaps the RF amplifier (Fig. 7). Because all the ground transmitters

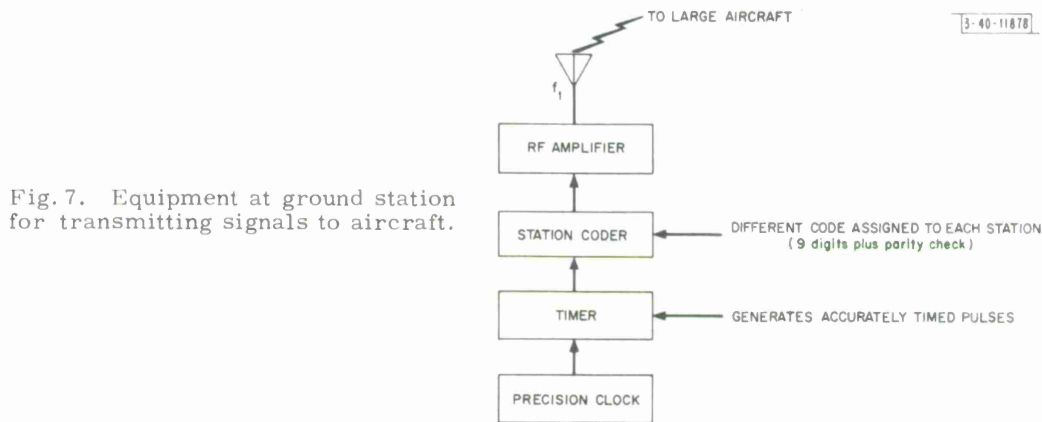


Fig. 7. Equipment at ground station for transmitting signals to aircraft.

operate at the same wavelength and carry identifying tags, it will be possible for a position determination to be made by employing signals from any combination of transmitters located at airports and at en route stations. To provide solid coverage throughout the United States for aircraft flying above a few thousand feet above the terrain, approximately 200 unattended stations will be needed to provide signals for midcourse navigation, an additional 300 situated within 10 miles of principal airports and 500 to 600 lower powered stations situated at or in close proximity (1 to 2 miles) to airports. Since these are unattended and relatively uncomplicated stations, this investment in ground support instrumentation does not seem inordinate and is comparable in number to the existing navigation aids it would replace.

E. Synchronization of Ground Stations

The U. S. Naval Observatory,¹² the National Bureau of Standards^{13,14} and industry have been active in the development and evaluation of precision timing clocks and synchronization techniques, and there is a voluminous bibliography in the literature.^{9,13} During the past year, radio astronomers using these clocks have conducted experiments at locations separated by intercontinental distances which involve the elimination of clock errors after completion of the measurements. Clocks are now sufficiently accurate to permit station synchronization for periods of approximately two days with timing uncertainties of about 100 nsec. Further refinements will, in time, reduce these errors to 10 nsec (Ref. 15). By means of satellites it has been possible to synchronize clocks in the United States and in Japan¹⁴ to within 1 msec, and recent work on collision avoidance systems^{16,17} provided new motivation for studies on the synchronization of precision clocks. In regions where LORAN C coverage is favorable, 100-nsec capability is obtainable.¹²

Existing cesium-beam clocks have a short term stability of less than 5 parts in 10^{-12} RMS frequency change for 1-sec averaging, and a long term stability of less than 2 parts in 10^{11} per

month. Looking 5 years ahead, it appears reasonable to synchronize a nation-wide grid of ground stations with synchronization errors over any 100-mile region of 50 nsec or less. In the same time period, the synchronization errors for those stations separated by short distances can probably be maintained to less than 10 nsec, providing transportable calibration standards can be employed every 20 to 30 days. This degree of synchronization capability appears more than adequate to fulfill the needs of the proposed ATC system.

Although it is evident that the desired degree of synchronization can be achieved by means of satellite or aircraft transponders, these systems are complex and may be subject to extraneous interference. Wideband radio links and cables would also be technically feasible, but they are complex and expensive and are not needed for the proposed system.

F. Coordinate System for Designating Position of Aircraft and Flight Tubes

The proposed system is based upon the assumption that each specific location (cell) in space can be designated by a discrete digital address. There are a number of possible coordinate systems, but the most obvious one for a world-wide system would employ the conventional latitude and longitude grid with an additional coordinate for altitude.

The fineness of the coordinate grid is determined by the precision of the position information needed by the aircraft during the landing and takeoff phases of flight. Since it would be desirable to locate aircraft position with an uncertainty which is small compared to the width of the runway, a cell size of approximately $4 \times 4 \times 4$ meters is proposed. The surface area of the earth is about 6×10^{14} square meters, and if it were divided into 4×4 meter resolution cells, there would be about 4×10^{13} cells. Two 24-bit binary numbers would be required to give each cell a unique address. In addition, if altitudes to 20,000 meters ($\sim 64,000$ feet) were to be coded into 4-meter increments, another 15 binary digits would be required, resulting in an address consisting of 63 digits ($24 + 24 + 15$).

However, in practice, aircraft seldom travel more than 3000 miles between flight legs and always have some knowledge of their position. Therefore, it will be possible to reduce the number of digits in the address substantially. If the maximum position uncertainty was as large as 150 miles, which is unlikely, then position in space with 4-meter granularity could be represented by a 47-digit number ($16 + 16 + 15$). Further simplification is possible. When an aircraft is not near an airport, a position designation (cell address) accurate to 60 meters (~ 200 feet) would be adequate and the address can be reduced to an identity code plus a 34-digit ($13 + 13 + 8$) address. When in close proximity to airports and accurate position designation is needed, the coarse digits of the address can be dropped to maintain the same overall word size.

Since computer technology continues to advance at a rapid rate and since the system requirements for data storage for computation are only nominal, there does not appear to be any critical need to minimize the information processing requirements of the airborne computer, and the coordinate system finally selected should be expandable to cover all regions of the world.

G. Instrumentation in Large Aircraft

The functions to be performed within the aircraft (discussed in Sec. II) can be accomplished by using state-of-the-art components and techniques. However, to attain a reliable low-cost system, each of the functional tasks as well as the design of each of the airborne components must be optimized and eventually evaluated by field trials. A detailed study of the utilization and transfer of data within each unit should, of course, precede any actual hardware construction.

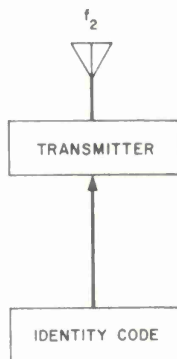
Studies to determine the optimum method for storing, retrieving and using the large quantities of data in the airborne computer memory file is an important facet of the problem. This file will contain the coordinates of each of the ground stations, as well as the total repertoire of information needed to generate the coordinates of each of the permissible flight paths. Because these data will change as new ground facilities are introduced and as other flight path routes are established, the data file should be stored on some form of magnetic disk or tape which can be readily erased and modified.

In regions where rapid maneuvers are not important or necessary, the data storage problem can be simplified by utilizing the computer to interpolate between sets of flight path coordinates in the data file. For example, if interpolation could be used for one-half the time during a 5-hour flight and if exact flight tube coordinates were stored for each 30-second time span of this $2\frac{1}{2}$ hour period, only about 300 sets of flight path coordinates would have to be placed into the file. Since these coordinates are recalled one at a time at a very slow rate, this is a trivial problem for conventional computer systems. If the remaining $2\frac{1}{2}$ hour portion of the flight path required new data points on an average of every 3 seconds, the data storage requirements are still very modest and many thousand complete flight path trajectories could be stored within a comparatively small storage unit.

The data storage problems are greatly simplified because it is possible to define a set of takeoff and landing procedures for any given class of aircraft, which when referenced to the runway coordinates, become independent of the location of the airport or the particular runway in use. For instance, there might be a straight departure "flight tube," a set of departures slightly to the right or left of the runway axis and perhaps a third set at slightly greater angles with respect to the runway. These five departure "flight tubes" perhaps with two or three altitude profiles could suffice for use at all airports. Then there could be a series of standard "flight tube" segments which would connect the departure phase to the initiation points of the midcourse "flight tubes." The optimum time-position path of the aircraft could be preplanned for each particular class of aircraft and there should be no problem in introducing variations, depending upon aircraft load, air temperature, runway altitude, etc. The important constraint, however, is that each position-time sequence be rigorously defined and carry a specific identification tag in the master file of permissible flight plans. If this is done, the designation of any particular flight profile, together with its time assignments, will have identical meaning both in the aircraft and at the FAA ground control centers.

When an aircraft is given a flight tube assignment, it will consist of several "flight tube" segments, each of which would be in the computer file and readily recalled when required. Because of the response time of the aircraft and pilot, new computations and information need be presented only at a comparatively low rate, probably not more than 5 or 10 times per second, even during landing and takeoff. A simple analysis of the demands placed upon the computer for the storage and generation of flight information indicates that by using state-of-the-art technology, comparatively simple, practical, flyable hardware can be manufactured.

The position determining unit, while having greater bandwidth and precision than existing LORAN C equipment, represents a modest increase in instrumentation sophistication. Substantial improvement in performance, is given by a digital computer that permits optimum use of the redundant information available when signals from more than four ground beacons are present. Since, in practice, there are likely to be 6 to 10 such beacons within range, the reliability of the information can be usefully enhanced. In addition, on-board flight instrumentation,



Low-power beacon transmits aircraft identity code each 10 seconds. Transmission is a short sequence of digits lasting about 2×10^{-6} second. Transmitter is unsynchronized (no clock) and should cost less than \$1000.

Fig. 8. Radio beacon in small aircraft.

Fig. 9. Small plane position determination (also backup system for large aircraft). Identity code transmitted by small aircraft informs ground stations to measure exact arrival time of pulses. These data remoted to control centers over telephone lines. Control center computes position coordinates of aircraft.

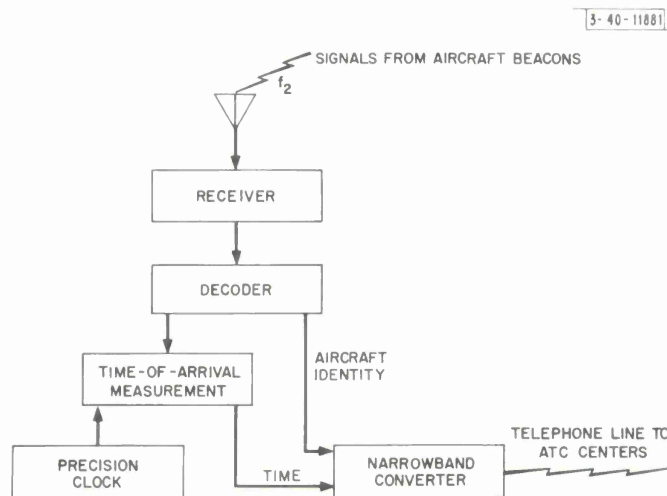
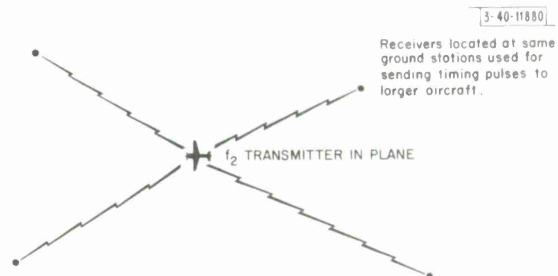


Fig. 10. Equipment at ground stations for decoding and measuring time of arrival of signals from small aircraft.

such as accelerometers, rate-of-turn gyros, electronic altimeters, etc., can be coupled into the computer to augment the information provided by the proposed radio navigation system.

In particular, there will be phases of the flight path, particularly when the aircraft is en route and away from airports, when the altitude data obtained from the position determining unit can be improved by the use of on-board barometric or electronic altimeters. Near airports where the ground station spacings are comparatively close, the radio navigation system should provide very accurate altitude data. The on-board computer can be programmed to optimally process all the available data, thereby providing improved accuracy and redundancy.

It has been estimated that the computational role to be carried out by the airborne computer is well within the capability of standard, commercially available, small digital computers now in production for ground-based applications. A computer with approximately 8000 words of memory, plus one or more slow-speed tape files and clock rates as low as 500 kHz will be adequate. These computers today cost about \$20,000 when packaged for ground use and their cost will undoubtedly be reduced and their capacity increased during the next five years.

The proposed system does not require a precision clock on board the aircraft. The airborne clock is used primarily for measuring the time differences between adjacent sets of ground-transmitter signals, and if all the successive readings are a little slow or a little fast, the position errors are not large. The airborne clock could tolerate stabilities of 1 part in 10^5 , which are readily achieved by existing quartz crystal oscillators.

It is also important to recognize that the airborne receiver is a fixed-tuned device with no knobs, since all the ground transmitters transmit on a common wavelength. This should lead to increased simplicity and reliability.

An airborne beacon capable of transmitting aircraft identity and aircraft position coordinates to the ground station at intervals of 5 to 10 seconds is required. To minimize multipath effects and reduce the likelihood that signals from aircraft will arrive at the ground receiver at the same time interval, the transmission durations must be short and the duty cycle low. A calculation based upon the use of 0-db gain antennas on the ground and in the aircraft, a 600°K receiver temperature and a 20-MHz signal bandwidth indicates that the peak power of the transmitter should be about 5 kw and the average power only a fraction of a watt. This performance is well within the current state-of-the-art.

V. TRAFFIC CONTROL FOR PRIVATE AIRCRAFT

While there are less than 3000 regularly scheduled commercial aircraft, nearly 200,000 private aircraft are in use and the number is growing rapidly. The large majority of these aircraft fly at altitudes below 10,000 feet and would normally use a different segment of air space than employed by the commercial airlines. Nevertheless, it is important that any future ATC system deal effectively with smaller aircraft which cannot afford expensive electronic instrumentation.

It is proposed that the network of ground stations previously described for transmitting synchronized timing signals to a large aircraft be used in a different mode to determine the position of smaller aircraft. Each small aircraft would carry a rudimentary beacon which would be turned on whenever the aircraft was in use. All the aircraft beacons (Fig. 8) would radiate on a common carrier frequency in the 2- to 6-GHz region of the spectrum. This carrier frequency could, in principle, be at the same frequency used for air-to-ground transmission by the commercial aircraft or they could be segregated in another region of the spectrum.

Each transmission from a small aircraft would consist of a sequence of about 20 pulses with a total duration of about 2 μ sec, which would carry the identity code of the aircraft. They would be modulated to have bandwidths of about 10 MHz. These transmissions would be received by the ground station network (Figs. 9 and 10), and the exact time of arrival of the signals, with respect to the master clocks at these stations, would be determined. These master clocks would be the same ones employed for the generation of the precisely synchronized timing signals used by the larger aircraft. This measurement of time of arrival plus the aircraft identification code would be converted to digital format and remoted via narrowband telephone lines to the regional ATC center. The ATC center would receive four or more sets of arrival time data for each aircraft transmission from the various stations in the ground network. It would process this information to locate the position of the aircraft accurately in space.

The system would be completely automatic in operation, since the beacons would transmit continuously and, in a sense, would be analogous to a flashing navigation light on the aircraft. The receipt, transmission and processing of this information would require no human intervention. The proposed system will not provide the pilot in the private aircraft with a continuous display of his precise position in space. He could utilize the standard navigation aids now available, or if desired, equip his plane with a receiver and manually operated display device for obtaining position fixes from the ground transmitter grid. Upon request, the ATC centers could provide precision fixes and navigation directions to the private pilots.

Since the majority of the commercial aircraft would normally fly within their assigned flight tubes, and since these flight tubes would rarely extend below 10,000 feet in altitude, except in proximity to airports, there will be large regions of the sky available for use by private and non-scheduled aviation. The "flight tubes" assigned to STOL (Short Take Off and Landing) aircraft will have to be a region of special interest for the private flyer. At airports where private planes would coexist with scheduled aircraft, the ground controller will have a completely up-dated and accurate picture at all times of the location of every aircraft in the vicinity. The ATC center will continuously compare the position of private aircraft with the commercial aircraft "flight tubes" and alert the ground controller of impending problems. He can then provide instructions to the private traffic in an effective manner, because his information is accurate, unambiguous and includes aircraft identity information. The control attainable from this system should be substantially superior to that available today.

In principle, a system could be devised for the large jet aircraft which operated in the same manner as the private aircraft system; one in which the position computation is carried out on the ground. However, systems of this type require continuous and rapid data transmission from the ground traffic control center to the aircraft, which to be practical must be broadcast on a common channel and not beamed specifically to each plane. This class of operation does not appear as well suited for use in high traffic density areas, particularly for those intervals of the flight path where great precision and a high data rate are needed, such as during landing and takeoff.

VI. EMERGENCY BACKUP CAPABILITY

In the event that the airborne equipment malfunctions or becomes completely inoperative, it will immediately be apparent both on the ground and in the aircraft. Deviations from the assigned "flight tube" by as little as a few hundred feet will be evident to the pilot and the ATC ground controller, since the position coordinates of the aircraft must progress sequentially and

in an orderly manner. The pilot can easily check the system response by introducing very modest flight maneuvers. Ground station synchronization errors will also be detected in the aircraft and on the ground because there are physical bounds on the permissible movement of an aircraft as it progresses through space. In the event of a ground station malfunction, all the aircraft in a given sector would have their position determinations modified in a very evident way. Under these conditions the local ATC center would turn off the defective station, since there would be a redundant number of ground stations.

As a backup capability, it is proposed that each commercial aircraft carry at least one and possibly two independently powered beacons of the type proposed for a private aircraft. These beacons would be activated whenever the main system became inoperative, and the pilot could be given navigation instructions by the ground controller. It would also be possible periodically to use the small beacon in parallel with the primary system for consistency checks. This degree of redundancy appears essential for any practical system.

VII. AIRPORT CAPACITY

The number of aircraft which can be accommodated at a given air terminal in a specified time interval will be determined to a large degree by: (a) the accuracy and data rate of the position information on all aircraft in the area, (b) the ability of aircraft to stay on their assigned flight paths, (c) the number of runways available for landings and takeoff, and (d) the scheduling and control capability of the ATC system. With the proposed system, adequate information will be available to permit the arrival times of each en route aircraft to be forecast and revised periodically and whenever new information becomes available.

Because there will be continuous knowledge in the ATC system of the precise position of all aircraft near an airport as well as their flight plans, it should be possible to operate with closer lateral spacings and time separations than is now acceptable. If flight operations from adjacent parallel runways are coordinated in time to minimize conflicts, runway spacings of about 1000 feet should be permissible. By coordinating the flight plans so that the aircraft diverge in space after takeoff, it should be possible to schedule operations on contiguous runways at time intervals of about 15 seconds (> 200 feet). Around each airport a number of special flight tubes would be reserved for emergency use. In the event of an unscheduled "pull out" maneuver during final approach, the aircraft would switch to one of several carefully planned computer subroutines which would place him in one of these emergency lanes. This information would automatically be brought to the attention of the controller via the routine operation of the data link system.

The implementation of this precision control concept should greatly increase the number of aircraft which may safely navigate near a busy airport and permit the addition of parallel runways 1000 feet apart at existing airports to enable many additional aircraft to be accommodated at a given field. It should be noted that the precision and data rate of the proposed system will be entirely adequate to allow aircraft to safely taxi on the ground under conditions approaching zero visibility and the control tower will know at all times the exact location of all parked, as well as moving, aircraft. This increased capability to move aircraft in and out of airports will undoubtedly result in bottlenecks in other aspects of air terminal operation (baggage, ground transportation, aircraft parking, etc.). However, the addition of buildings and parking facilities at a single airport would have distinct advantages over a network of less convenient satellite airports, since these new airports, if they are serving a common city, will still largely require the use of common air space.

In the proximity of airports it should be possible for the equipment in the aircraft to measure position in directions perpendicular to the flight tube with an uncertainty of 10 feet or less. The progress along the flight tube can probably be maintained with an uncertainty which should rarely be greater than about 5 seconds. At the speeds used for landing and takeoff, this time error corresponds to a distance along the flight path of less than 1500 feet. Since with the proposed system the only aircraft flying near the landing and takeoff sectors near the runway would be proceeding in precisely defined directions, it should be possible to operate aircraft safely at much closer spacings than is presently allowable, providing they are staggered in time on parallel approaches.

At the present time, parallel runways at airports are, for safety reasons, separated by distances of approximately 5000 feet. The precision provided by the proposed system should make it possible to place about two or three additional runways within this 5000-foot spacing without compromising safety considerations. This should be possible because the aircraft on contiguous landing strips would also be time sequenced in a precise manner. Therefore, it seems reasonable that the number of arrivals and departures at a given airport can be tripled, providing adequate runways are added.

It would seem preferable to increase the flow of air traffic by augmentation of existing runways and other facilities at existing airports rather than by constructing separate facilities at locations which are less convenient for serving the traveling public. It is conceivable that with a proper ATC system airports could employ two or even three complete compounds of widely spaced passenger terminals at edges of the airport. With this configuration, the ATC problem would not be substantially more complicated, since airports even 50 miles away must be completely integrated into an effective control system.

VIII. COLLISION AVOIDANCE

In the proposed system the likelihood of midair collision should be negligibly small because all the commercial traffic would be flying along preassigned routes on rigorous schedules, and private traffic would be restricted to other air corridors and altitude regions. However, if desired, it would be possible to augment the system with an anticollision capability which was independent of the ATC centers.

Under normal operation, each aircraft will be transmitting its identity and the coordinates of the "cell in space" which it occupied. This transmission would be on the common channel used for all air-to-ground transmissions. Because of the very short duty cycle of each transmission and the unsynchronized nature of the transmissions, interference will not be an important problem. By equipping commercial aircraft with a receiver capable of monitoring the air-to-ground channel, it could obtain reports indicating the coordinates of all other aircraft in the vicinity. These reports would be processed in the airborne computer and those aircraft having coordinates which could conceivably threaten collision could rapidly be identified. Since reports from these aircraft will be arriving at least once every 5 seconds, trajectories could be determined for these aircraft of interest and if dangerous situations appear to be developing, appropriate information could be presented to the pilot.

The prevention of collision between large and private aircraft would be achieved by carefully segregating permissible flight patterns and by exact knowledge by the ground controller of the position and identity of each and every aircraft. Since the commercial aircraft will be flying along precisely planned routes, the controller's task in anticipating difficulties will be enormously

simplified when contrasted to the present situation. The responsibility for avoiding air-to-air collision between two private aircraft will reside with the pilots, but the controller will have computer-aided information to enable him to inform the pilots of other aircraft in his vicinity. The collision avoidance capability of the proposed system appears to obviate the requirement for the airborne collision avoidance system (CAS) now under development.

IX. ESTIMATE OF EQUIPMENT COST

During the past decade there have been very significant improvements in the reliability and in the size and power requirements of electronic equipment. These improvements result in large part from improved solid state components and from improved design, fabrication and testing techniques. There have also been moderate but nevertheless significant reductions in equipment cost. Although it is difficult to estimate accurately the cost of the various components of the proposed system, because the cost will depend upon the quantities of units procured at a single time, it is nevertheless possible to make crude estimates.

A. Ground Installations

In the proposed system there are moderate quantities of ground equipment in the navigation grid which utilize common functional modules. If 100-percent redundancy in equipment is provided, production quantities may eventually reach a thousand or more units. The ground stations differ primarily only with respect to the power output level of the transmitter amplifier. The equipment needed at a ground station when constructed with contemporary electronic components could easily be mounted within a single 6-foot-high standard electronic rack. The cost of this equipment, together with a complete spare for redundancy, is estimated to be less than \$30,000 in moderate production quantities. Since many of these ground transmitter installations can be located at existing communication and navigation aid sites, the cost for the prime power supply, buildings, protective fences, etc., is difficult to estimate but should not exceed \$10,000 per site.

The current ground-to-air and air-to-ground communications network would continue to be employed, as would the computers and display consoles at the ATC sector centers. Additional narrowband ground communication circuits would be needed to relay the air-to-ground beacon messages to the ATC centers.

A very rough estimate indicates that the cost of a complete nation-wide ground-based system consisting of approximately 1000 beacons, about half of which are located near airports, would not exceed \$100 million. This cost is small compared with the cost of the present FAA investment in ground stations, radars, navigation aids and communication facilities.

B. Aircraft Equipment

The most expensive element of the installation on a large jet aircraft would be the airborne digital computer, which in this time period of interest is estimated to cost approximately \$15,000. The cost of the other elements of the airborne system for a large commercial jet should not exceed \$15,000. With 100-percent redundancy, the overall cost of the electronic equipment in the aircraft is estimated to be less than \$75,000. However, this new installation could replace some of the navigation aids, beacons and other electronic units now carried on these aircraft. Because the proposed installation should substantially enhance the ability of aircraft to transport passengers with a minimum of schedule delays and interruptions due to weather, the increased productivity of the aircraft should compensate for these added costs in a relatively short span of time.

The only electronic component needed in private and small general aviation aircraft, other than the standard voice communication radio, would be a small pulsed beacon transmitter coded with the identity of the aircraft. In production, this equipment is estimated to cost between \$500 and \$1000.

X. SUMMARY

A system for navigation, data reporting and traffic control is described which will enable aircraft to fly safely and on schedule in areas with high traffic density. In the proposed concept, aircraft would no longer be concentrated along airway corridors, but would be distributed in air space and fly along a network of nonintersecting "flight tubes."

By means of automatic data reporting equipment, the coordinates and identity of every aircraft in the sky will be continuously available at the ATC centers. The proposed system permits the ground controllers to be in "shunt" and not in "series" with the movement of aircraft and increases their ability to monitor the rapidly changing air traffic patterns.

Aircraft will be able to arrive at airports precisely at the time when their preassigned runway space is available. "Stacking" near airports will be eliminated. Near-simultaneous use of runways spaced about 1000 feet apart will be possible and this should allow many more landings and departures from existing airports. Also, aircraft will be able to take off and land under conditions of near-zero visibility.

The system incorporates high redundancy on the ground and an emergency mode in all aircraft. Equipment malfunctions will readily be apparent both in the aircraft and on the ground.

The precision timing equipment, airborne digital computers and nanosecond pulse technology, upon which this concept is based, are all within the current state of the art.

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13. ABSTRACT		
<p>To increase the number of aircraft which can operate safely in high traffic areas and to expedite traffic at busy airports, it is proposed that each commercial flight travel from terminal to terminal along a "flight tube" reserved for its exclusive use. To make this possible, an instrumentation system is described which would continuously provide an aircraft with both accurate position information and with instructions for progressing along any selected "flight tube." Every few seconds each aircraft would report its identity, position and altitude via a digital air-to-ground data link to the Air Traffic Control (ATC) centers. This accurate, unambiguous information will enable the centers to monitor automatically all aircraft movements, and any deviation of an aircraft from an assigned flight plan would be detected by the computer and brought to the attention of the appropriate ATC controller.</p> <p>Because the navigation and position reporting would be automatic, the work loads now experienced by the air crews and the ground controllers would be reduced. Congestion at airports and stacking of aircraft near airports would be minimized by continuous forecasts of runway availability and be en route adjustments of the time of arrival of an aircraft at its assigned runway. A compatible capability, at lower cost, is proposed to enable the ATC system to track automatically all private and general-aviation aircraft.</p> <p>The proposed navigation and data reporting system would also function during takeoff and landing as well as en route, and would obviate the need for the existing network of omni-ranges, localizer beacons, ground radars, landing systems and other navigation aids. It would provide data of high quality on aircraft movements and enable the computerized data processing system now being introduced throughout the country by the Federal Aviation Administration to operate with greater effectiveness. The precise navigation, control and scheduling which is provided by the proposed system would enable higher densities of aircraft to operate safely and would permit new runways within the confines of existing airports to be used effectively.</p>		
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